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Technical Report 470

DETERMINATION OF INTEGRATED OPTICAL THICKNESS OF CLOUDS FROM LUNAR IRRADIANCE MEASUREMENTS

MG Ceruti

15 October 1979

Final Report: 15 June - 15 October 1979

AD A

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NAVAL OCEAN SYSTEMS CENTER
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ADMINISTRATIVE INFORMATION

This report was prepared by the author while working for Code 8114, Naval Ocean Systems Center, San Diego, CA under NOSC CM06, 11402 N, XO 793-SB. This project was initiated and supported by the efforts of Dr MB White of the Office of Naval Research, Boston, MA and by CDR T Wiener and Dr S Karp of DARPA STO, Washington, D.C. Gratitude is also extended to blue-green cloud propagation project manager, KJ Kelley, and to LB Stotts, Dr GC Mooradian, Dr M Geller, DH Stephens, Dr RP Bocker, RD Anderson, RF Howarth, R Krautwald, and R Reyes of the Naval Ocean Systems Center.

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A procedure is suggested to obtain the effective optical thickness (τ) of clouds by measuring the atmospheric transmission of moonlight both with and without cloud cover.

The optical thickness is calculated from the transmission using a theory of RE Danielson, DR Moore and HC van de Hulst (The Transfer of Visible Radiation Through Clouds, J. Atmosph. Sci., 26, 1078 (1969)), later modified by EA Bucher, (Computer Simulation of Light Pulse Propagation for Communications Through Thick Clouds, Applied Optics, 12, No. 10, p 2391-2400 (1973)). By using a wide field of view receiver to measure the irradiance, one obtains a spatial averaged value of τ, rather than a point measurement. Therefore, this method of cloud optical thickness determination may be more reliable than some previously used methods.

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BACKGROUND

One of the most serious problems facing the Navy today is that of transferring information to submarines without affecting their operational capabilities. Ideally, such a communications connectivity should be available at all operating speeds and depths, and should not require any external receiver which would compromise the submarine's strategic or tactical function. Until recently, most attempts at solving this problem have focused on systems that use the lower end of the electromagnetic spectrum for transmission of the desired information (ie, elf, vlf, etc). The advent of high power ultraviolet-visible lasers has changed this spectral emphasis to include optical frequencies. In particular, the Navy and the Defense Advanced Research Projects Agency have been jointly investigating the possibility of an optical solution for strategic communications.[1] The intent has been to assess the practicality and suitability of optical technology to solve the strategic communications problem. The approach involves detailed analyses and experimentation in the areas of optical engineering, channel characterizations, and critical component technology development.[1,2] One of the investigations pursued in the channel characterization portion of the program was on the effect of clouds on short-pulse, optical plane-wave propagation through the atmosphere.[2,3,4] This report describes results obtained during one aspect of that investigation. More specifically, a partial set of inferred integrated optical thickness values derived from lunar irradiance measurements of the laser-illuminated cloud layer used in the Downlink Laser Cloud Propagation Experiment performed in Kauai, Hawaii, during August and September 1979 is reported.[2,3]

TECHNICAL INTRODUCTION

When a plane wave laser pulse is incident on a thick, plane-parallel cloud layer, the resultant pulse is severely degraded relative to the incident illumination profile because of the multiple scattering which occurs within the cloud. In more certain terms, an initial narrow pulse plane wave will exit the cloud layer decollimated and attenuated, with the incident pulse

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1. Karp, S, A Test Plan for Determining the Feasibility of Optical Satellite Communications Through Clouds at Visible Frequencies, NOSC TN 279, 1 July 1978.
2. Technical Advisor to the Strategic Blue-Green Optical Communications Program Joint Coordinating Committee, Naval Blue-Green Single Pulse Downlink Propagation Model, NOSC TR 387, Jan 1979.
3. Technical Advisor to the Strategic Blue-Green Optical Communications Program Joint Coordinating Committee, Strategic Blue-Green Optical Communications Program Plan, NOSC Technical Document 269, 16 July 1979.
4. Hostetter, GR, Test Plan May 1, 1979 Downlink Laser Cloud Experiment, Contract #N00014-78-C-0716, GTE Sylvania, Inc.

shape greatly lengthened and distorted.[5,6] The magnitude of these effects depends on the cloud layer's physical thickness, optical thickness, solar phase function and rms scatter angle (or, conversely, the average cosine of scattering).[2,7,8] Several analytical[8-18] and Monte Carlo based[7,19,20] treatments of all or part of the above exist in the literature. Many of the above have been used in the Navy Single Pulse Downlink Propagation Model[2] to simulate the channel effects incurred by both the ground-based and space-based laser communications concepts being pursued in the Strategic Blue-Green

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5. Stotts, LB, Closed Form Expression for Optical Pulse Broadening in Multiple-Scattering Media, Applied Optics, 17, No. 4,504 (1978).
6. Dell-Imagine, RA, A Study of Multiple Scattering of Optical Radiation with Application to Laser Communications, in Advances in Communication Systems, vol II, edited by VA Balakrishnar (Academic, New York, 1966). p 1.
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13. Ishimaru, A, and Hong, ST, Multiple Scattering Effects on Coherent Bandwidth and Pulse Distortion of a Wave Propagating in a Random Distribution of Particles, Radio Sci. 10, 637 (1975).
14. Hong, ST, and Ishimaru, A, Two Frequency Mutual Coherence Function, Coherence Bandwidth, and Coherence Time of Millimeter and Optical Waves in Rain, Fog, and Turbulence, Radio Sci. 11, No. 6,501 (1976).
15. Stotts, LB, The Radiance Produced by Laser Radiation Traversing a Particulate Multiple-Scattering Medium, J. Opt. Soc. Am., 67, No. 6, p 815-19 (1977).
16. Ishimaru, A, Theory and Application of Wave Propagation and Scattering in Random Media, Proceedings of IEEE, 65, No. 7, p 1030-61 (1977).
17. Fried, DL, Propagation of the Mutual Coherence Function for an Infinite Plane Wave Through a Turbid Medium, Optics Letters, 1, No. 3, p 104-6 (1977).
18. Lutomirski, RF, Atmospheric Degradation of Electro-Optical System Performance, Applied Optics, 17, No. 24, p 3915-21 (1978).
19. Plass, GN, and Kattawar, GW, Monte Carlo Calculations of Light Scattering from Clouds, Applied Optics, 7, No. 3, p 415-19 (1968).
20. Bucher, EA, Propagation Models for Optical Communications Through Fog and Clouds, Proceedings of the National Electronic Conference, vol 29, p 180-185 (1974).

Optical Communications Program. Unfortunately, none of the above have been experimentally verified. Hence, a technical uncertainty exists in any performance estimate produced in the system engineering portion of that program.

To reduce this uncertainty, the program's Joint Coordinating Committee initiated an experimental effort[3,4] to measure the transmission and multipath time spread incurred when traversing actual atmospheric clouds.[3] The participants involved in the experiment were GTE Sylvania; HSS, Inc.; and the Naval Ocean Systems Center (NOSC), with NOSC responsible for the meteorological characterization portion of the experiment. Because of the importance and magnitude of the experiments, NOSC felt that an alternative characterization of a cloud layer's optical thickness was desirable and that, since inhomogeneities in the cloud layers were anticipated, an integrated optical thickness characterization technique should be employed.

Gary Lee, et al, of McDonnell Douglas Corp. suggested that a method using measured solar radiance levels could be used to infer the cloud's integrated optical thickness. (See reference 1, appendix B.) This procedure is general enough to apply to lunar irradiance as well, if lunar properties such as moon phase, and earth-moon distance are accounted for. The author was tasked to design the experiment, perform the on-site measurements, reduce the data, and document the findings. This report provides that documentation.

THEORY OF OPTICAL THICKNESS DETERMINATION USING LUNAR IRRADIANCE MEASUREMENTS

The amount of radiant energy flux from the moon, as measured on a flat horizontal surface, depends on the following factors:

1. Moon phase; a full moon yields the most light.[21,22]

2. The angle of the moon's position relative to the zenith; maximum brightness is observed when the moon is directly overhead.[21,22]

3. The earth/moon distance; the light flux is the most intense at lunar perigee.[22]

4. The matter in the lunar path between the moon and the detector, such as particulate scattering from absorption and clouds. Variation of absorption and scattering due to atmospheric changes is to be constant throughout the time the lunar irradiance measurements are taken.

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21. Biberman, LM, Dunkelman, L, Fickett, ML, and Finke, RG, Levels of Nocturnal Illumination, Appendix by D. R. E. Brown, Institute for Defense Analysis Research, copy 109/200, Contract SO-50, Task T-36.
22. Bond, DS, and Henderson, FP, The Conquest of Darkness, AD 346297, Defense Documentation Center, Alexandria, VA, July 1963.

Measurement of the lunar irradiance with a clear sky and measurement of the lunar irradiance with clouds in the light path can be used to determine the scattering and absorption due to clouds if the moon's phase, the moon's position, and earth/moon distance are properly accounted for. The difference between these two irradiance measurements is the essence of the experiment. An in depth discussion of the theory and method are presented in reference 1.

The chief advantage of this method of determining optical thickness is that a spatially averaged value of irradiance is obtained. Thus, if the receiver field of view contained some patchy clouds and some clear sky, the value of irradiance observed would be approximately equal to what one would see if the visible cloud material (of sufficient thickness) had been equally distributed over the entire field of view. This will not work for clouds whose optical thickness is less than about 20, because the method relies on the van de Hulst equation[7] to derive τ from a transmission value.

MEASUREMENT PROCEDURE

Values of lunar irradiance were obtained utilizing the following procedure:

The irradiance receiver was mounted on a tripod, exposed to the lunar sky with a zenith orientation. Values of lunar irradiance were monitored at various times throughout the night, as was the position of the moon at the time of each measurement. The values obtained were used in conjunction with the theory to normalize the observed irradiance measurements for cloudy conditions relative to those taken under clear sky conditions.

Simultaneous with the lunar irradiance measurements were measurements of direct laser pulse propagation through clouds. The laser was mounted on an aircraft and pulsed at 10 Hz. The aircraft was flown above the clouds and over the test site. The position of the aircraft was monitored continuously throughout the aircraft fly bys.

Figure 1 indicates the geometry of both the aircraft laser and the lunar irradiance measurements. The laser beam was spread upon exit from the aircraft and further dispersed by the clouds so that any laser light indicating the irradiance receiver was negligible and not detectable above the moonlight background.

Measurements were taken for the laser experiment during the last week of August and the first three weeks of September 1979. Lunar irradiance measurements were made between 5 September and 12 September 1979. These experiments were conducted simultaneously on the Island of Kauai on Hawaii.

EQUIPMENT CONFIGURATION

The irradiance receiver consisted of an RCA 4517 photomultiplier tube, a high-voltage power supply, and a preamplifier buffer mounted in a waterproof

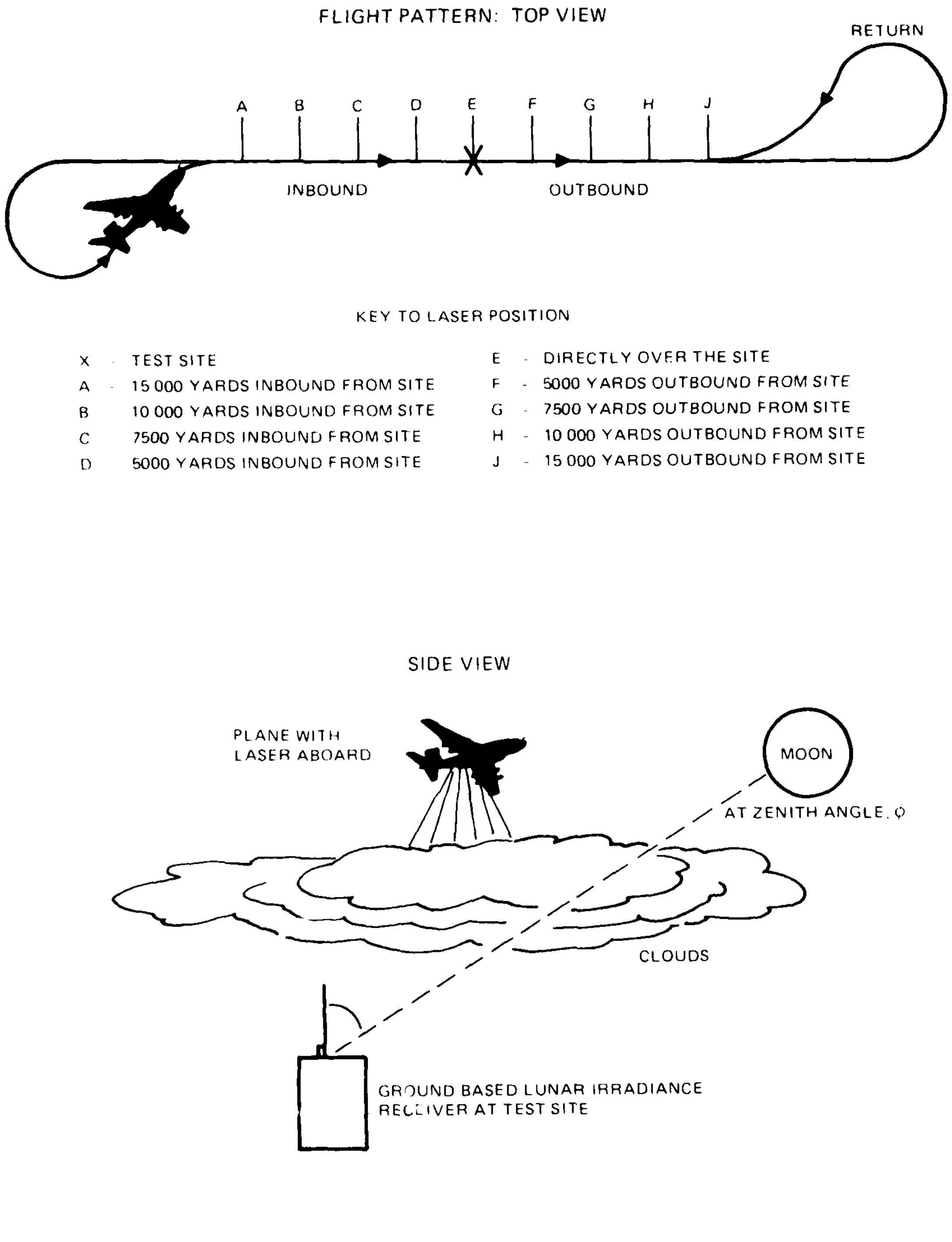

Figure 1. Geometry of experiment.

housing.[23] In addition, a 45° field of view limiter, a diffuser, and a Wratten filter were employed on the receiver. The purpose of the diffuser was to randomize the direction of the incoming light rays by scattering and thus to provide a spatially averaged effect. Figure 2 shows the apparatus along with the other electronic equipment.

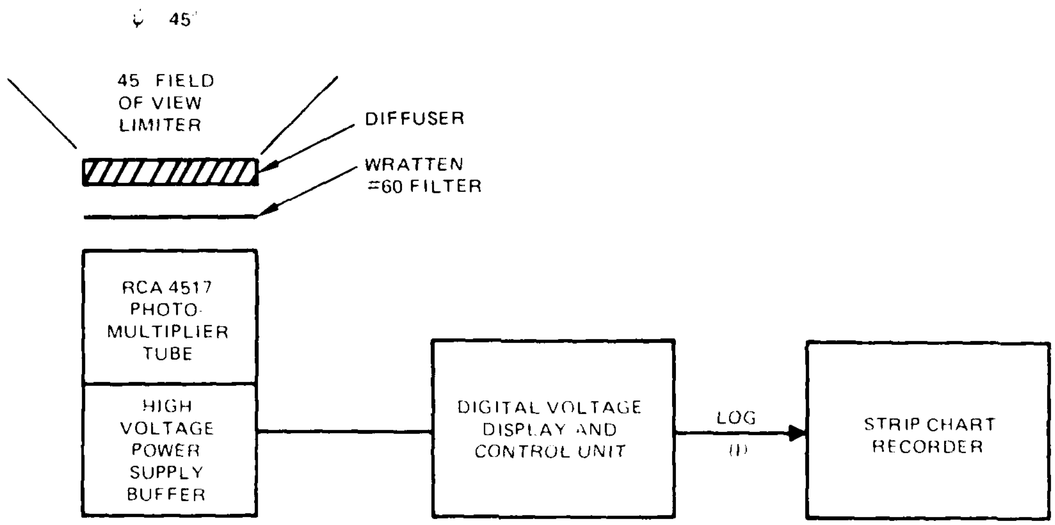

Figure 2. Experimental apparatus.

The 45° field of view limitation was used to occlude any stray light originating from city street lights or automotive headlights. Thus, the measurement was not one of irradiance in the strict sense of the definition which requires a 180° field of view. Therefore, a factor of 2 must be applied to all voltage measurements representing cloud attenuated lunar irradiance levels. This is the coefficient which appears in equation 5. Details of the derivation can be found in appendix A.

The detector's response was calibrated over the entire dynamic range of its operation using a standard lamp type P-101 Electro Optics Associates, and was found to be linear. This calibration was done in the laboratory with neutral density filters of varying strengths before the field experiments were begun.

Data acquisition in the field was accomplished by reading the digital voltage display on the control unit and simultaneously storing the base 10 log using a strip chart recorder. The time and laser position (fig 1) of each measurement were noted in order to concurrently correlate the results with those of the other experiments. The moon's angle of elevation was also monitored to the nearest degree.

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23. Smith, RC, An Underwater Spectral Irradiance Collector, J. of Marine Res., 27, 341, 1969.

DATA REDUCTION

The method of obtaining a transmission value consisted of recording the voltage, V_1 (which is proportional to irradiance, during conditions of cloud cover), with the axis of the detector pointed at the zenith (figure 1).

A standard reference voltage, $V_o(1)$ at a zenith angle of ϕ_R was recorded on 1 September 1979, when the moon was observed in a totally clear sky. The presence of clouds in the detector's field-of-view during a calibration measurement would cause scattered light, in addition to the direct moonlight beam, to enter the detector and thus would lead to an erroneously high value for the reference irradiance.

In order to use this reference value to calculate transmissions from irradiance data acquired on subsequent nights, it is necessary to correct it for changes in moon phase, moon zenith angle, and earth-moon distance. These corrections are summarized in equation (1).

$$V_o(N) = V_o(1)\,\frac{P(N)Z(\phi)\ D(N)}{P(1)Z(\phi_R)D(1)} \tag{1}$$

In equation (1) $V_o(N)$ is the voltage to be used as a reference on night N, where N is the day in the month of September in this case. $V_o(N)$ is proportional to the irradiance which would have been observed from the moon if the sky had been totally free of clouds. P(N) is a factor influencing the irradiance which depends upon the phase of the moon on a given night, N. $P(N)=P(6)=1.0$ for a full moon, which in this case occurred on 9/6/79. When no moon appears in the sky, $P(N)=0$. On the other nights, the lunar irradiance will be a fraction of that of the full moon, measurements of which are detailed elsewhere in the literature.[21]

Two least square polynomial fits to these data are given by equations (2) and (3).

$$P_1(N) = 10.1787 - 1.5813\ (N + 31) + 9.2956 \times 10^{-2}\ (N + 31)^2$$
$$-2.4618 \times 10^{-3}\ (N + 31)^3 + 2.4894 \times 10^{-5}\ (N + 31)^4; \tag{2}$$

$$P_2(N) = -2.6579 \times 10^3 + 2.6784 \times 10^2\ (N + 31) - 1.0052 \times 10^1\ (N + 31)^2$$
$$+1.6733 \times 10^{-1}\ (N + 31)^3 - 1.0416 \times 10^{-3}\ (N + 31)^2 \tag{3}$$

N is equal to the day in the month of September when a given experiment was performed. Equation (2) is valid when the moon is waxing, in this case between 9/1/79 and 9/6/79; whereas, equation (3) applies during the time period between 9/7/79 and 9/12/79, when the moon was waning.

$Z(\phi)$ is proportional to the irradiance measured on a horizontal surface at a given zenith angle, ϕ. Because, to a very good first approximation, the spectral distribution of reflected light from the moon is equal to that emitted from the sun, solar data can be used for $Z(\phi)$ for applications where a ratio $Z(\phi_1)/Z(\phi_2)$ is implemented.[22] $Z(\phi)$ is given by:

$$\log(Z(\phi)) = 2.8685 + 1.9834\left(\frac{\pi}{2} - \phi\right) - 1.0785\left(\frac{\pi}{2} - \phi\right)^2$$

$$+ 1.7092 \times 10^{-1}\left(\frac{\pi}{2} - \phi\right)^3 + 1.2418 \times 10^{-2}\left(\frac{\pi}{2} - \phi\right)^4 \qquad (4)$$

and is most accurate for zenith angles between 0 and 47 degrees, with ϕ in units of radians. The data for which this expression is a fit were also taken from the literature.[21]

$D(N)$ expresses the change in illumination resulting from the variation in the earth/moon distance. At the lunar perigee, the moonlight is 0.26 times brighter than at the apogee.[22]

The transmissions were obtained by normalizing the corrected voltage readings for the cloud experiments with the $V_o(N)$ computed from equation (2).

$$T = \frac{2Vi}{V_o(N)} \qquad (5)$$

where T = transmission. Values of τ, the optical thickness, can then be computed using an equation due to van de Hulst[7] and later improved at NOSC to be more accurate at large zenith angles.

$$\tau = \frac{A(\phi_i)}{0.125T} - 11.36 \qquad (6)$$

Here $\langle\cos\theta\rangle$, the average cosine of the scattering angle, has been taken to be 0.875. ϕ is the zenith angle of the moon, in radians. (See appendix B.)

$$A(\phi_i) = 1.69 - .5513\,\phi_i + 2.7173\,\phi_i^2 - 6.9866\,\phi_i^3 + 7.1446\,\phi_i^4 \qquad (7)$$

$$- 3.4249\,\phi_i^5 + 0.6155\,\phi_i^6$$

FINDINGS

The findings are in accordance with the preceding analysis. Transmission values are given in tables 1 through 5. The inferred values of τ for the reduced measurement data are listed in tables 6 through 10.

The values are tabulated by GTE Sylvania run number and position. The run number refers to the value assigned to a particular overflight of the aircraft containing the laser and is used as standard indicator for correlation between the various experiments conducted at Kauai. Laser position is that indicated in figure 1.

No reliable data were obtained during conditions of rain and clear sky, except for the reference. Some run numbers are therefore omitted when there were clouds in the sky surrounding a clear path between the moon and the detector. The data for these particular cases are not valid, for reasons mentioned in the previous section and have also been omitted.

Values of τ, below 20, are probably not very accurate because those clouds we observed during the indicated time period were too thin to be adequately described by the van de Hulst equation, which operates in the diffusion regime. Although this is the case, values of optical thickness above 1 are listed for the purpose of comparing these results to numbers for τ inferred from the data obtained in concurrent experiments.

The wide range of values obtained for the optical thicknesses in tables 6 through 10 reflects the wide variety of clouds observed over the test site. Similarly, the variation of optical thickness within a single run also reflects the rapidly changing and dynamic behavior of the clouds we encountered.

Measurements obtained when the moon was full, or near full, are more reliable than those acquired on nights with a lesser degree of lunar illumination.

There is a random error of about 5% on each value of the optical thickness. The background radiation from the night sky and stars was neglected, as were effects originating from changes in the absorption of the atmosphere from day to day. This is expected to be a fairly good assumption because there is not much atmosphere absorption in the spectral region of 530 nm. Also neglected was the very small change in moon phase over the course of one night's data acquisition. The cosine of the scattering angle was assumed to take the value of 0.875 (reference 7 and appendix B).

RECOMMENDATIONS

The results presented in tables 1 through 10 are for only one method of measurement transmission and optical thickness of clouds. To determine if this is an appropriate method of measuring integrated optical thickness of clouds, the results should be compared with other measurements and postulated theory for cloud optical thickness. Hence, the following recommendations are made.

1. Compare optical thickness values measured by this method to those obtained simultaneously from the Knollenberg particle size spectrometer during the blue-green laser cloud propagation experiments performed on Kauai, HI from 13 August through 21 September 1979.[2,3,4]

2. Correlate the multipath time spread calculated from the inferred optical thicknesses of this method with those simultaneous pulse stretching results to be contained in the final report of the Downlink Laser Cloud Propagation Experiment. Several models for multipath time spreading (eg, references 2 and 5) currently exist for the comparison.

3. Compare pulse shapes predicted by Monte Carlo computer simulation calculations on photons transmitted through clouds to pulse shapes predicted by the present values of optical thickness and transmission.

Table 1. Cloud Transmission Values from Irradiance Measurements.

Data Acquisition Period: 9/5/79, 21:15 - 23:25

Laser Position \ Sylvania Run #		93	94	95	96	97	98	100	103	104	105
A	TRANSMISSION	--	--		0.816	0.527	0.902	0.986	--	--	--
B		0.896	0.459	--	0.734	0.559	0.935	0.914	--	0.839	0.774
C		--	--	--	0.757	0.593	0.961	--	--	0.767	0.782
D		0.652	0.462	0.992	0.730	0.646	0.984	0.822	0.950	0.725	0.782
E		--	0.400	0.909	0.684	0.814	--	0.774	--	0.663	0.761
F		0.458	0.400	0.861	0.649	0.975	--	0.698	--	0.656	0.732
G		0.465	0.511	0.850	0.634	--	--	--	--	0.703	0.723
H		--	--	--	0.626	--	--	0.641	--	0.814	0.725
J		--	--	0.850	--	--	--	--	--	0.781	0.769
Approximate Time (hr)		21:15	21:17	21:27	21:33	21:41	21:47	22:02	22:20	--	--

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 2. Cloud Transmission Values from Irradiance Measurements.

Data Acquisition Period: 9/6/79; 24:19 - 9/7/79; 2:50

Laser Position \ Sylvania Run #		114	115	116	117	118	119	120*	121	122	124
A	TRANSMISSION	--	--	0.781	--	--	0.524	0.176	0.502	0.580	--
B		--	--	0.739	0.531	0.639	0.553	0.188	0.466	0.611	--
C		--	--	--	0.557	0.589	0.561	0.207	0.445	0.631	--
D		0.944	--	--	0.619	0.557	0.552	0.233	0.419	0.654	--
E		--	0.915	--	0.758	0.543	0.529	0.282	0.390	0.684	0.983
F		--	--	--	--	0.609	0.510	0.327	--	0.684	--
G		--	--	--	0.882	--	0.504	0.353	--	0.684	--
H		--	--	0.943	0.985	--	0.496	0.372	0.429	0.684	--
J		--	--	0.973	--	0.588	0.468	0.401	0.412	0.652	--
Approximate Time (hr)		24:19	--	24:23	--	24:45	--	--	1:02	--	1:18

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound

E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

*Rain

Table 2. Cloud Transmission Values from Irradiance Measurements (continued).

Data Acquisition Period: 9/6/79; 24:19 - 9/7/79; 2:50

Laser Position \ Sylvania Run #		126	127	128	129	130	132	134	136	138
A	TRANSMISSION	--	0.714	0.770	0.264	--	--	0.936	0.779	0.689
B		0.986	--	0.741	0.289	--	--	0.468	--	0.951
C		0.699	--	0.728	0.304	--	--	0.423	--	--
D		0.612	--	0.833	0.316	0.991	--	--	--	--
E		0.525	--	0.787	0.341	0.903	0.949	--	0.859	--
F		0.682	--	0.658	0.385	0.909	--	--	--	--
G		0.643	--	0.645	0.409	0.919	--	--	0.969	--
H		0.610	--	0.640	0.423	0.884	--	--	0.724	--
J		0.545	--	0.635	0.471	0.893	--	--	0.561	--
Approximate Time (hr)			1:41	1:48	1:55	2:04	--	2:27	2:41	2:50

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 3. Cloud Transmission Values from Irradiance Measurements.

Data Acquisition Period: 9/7/79; 22:38 - 9/8/79; 1:17

Laser Position \ Sylvania Run #		142	143	147	148	149	150	151
A	TRANSMISSION	--	0.328	0.208	0.409	0.290	--	--
B		0.390	0.316	0.207	0.448	0.320	0.955	0.654
C		--	0.318	0.208	0.465	0.341	0.911	--
D		0.391	0.326	0.218	0.465	0.353	0.885	--
E		0.396	0.360	0.268	0.473	0.385	0.861	--
F		0.414	0.487	0.456	0.443	0.427	0.857	--
G		0.425	0.515	0.483	0.412	0.455	0.861	--
H		0.433	0.537	0.465	0.386	0.491	0.864	--
J		0.461	0.573	0.381	0.338	0.564	0.874	--
Approximate Time (hr)		22:38	22:46	23:09	23:15	23:20	23:27	23:35

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 3. Cloud Transmission Values from Irradiance Measurements (continued).

Data Acquisition Period: 9/7/79; 22:38 - 9/8/79; 1:17

Laser Position \ Sylvania Run #		152	154	155	158	159	160
A	TRANSMISSION	--	--	--	0.831	0.440	--
B		0.882	0.951	--	0.759	0.535	0.629
C		0.532	--	--	0.795	0.301	0.600
D		0.666	--	--	0.994	0.299	0.570
E		--	--	--	--	0.284	0.519
F		--	--	0.920	--	0.314	0.489
G		0.945	--	0.766	--	0.308	0.480
H		0.481	--	0.758	--	0.315	0.467
J		0.392	--	--	0.740	0.314	0.437
Approximate Time (hr)		23:41	23:53	24:00	00:18	00:24	00:30

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 3. Cloud Transmission Values from Irradiance Measurements (continued).

Data Acquisition Period: 9/7/79; 22:38 - 9/8/79; 1:17

Laser Position \ Sylvania Run #		161	162	163	165	166	167	168
A	TRANSMISSION	0.284	--	--	0.391	0.354	0.277	0.413
B		0.313	0.403	--	0.409	0.338	0.344	0.401
C		0.316	0.390	--	0.418	0.325	0.370	0.413
D		0.320	0.371	0.879	0.431	0.321	0.376	0.435
E		0.290	0.342	--	0.458	0.310	0.376	0.533
F		0.325	0.340	--	0.479	0.305	0.379	0.928
G		0.333	0.348	--	0.488	0.301	0.396	0.760
H		0.200	0.365	--	0.492	0.291	0.435	0.771
J		--	0.384	--	0.490	0.289	0.444	--
Approximate Time (hr)		00:37	00:42	00:47	1:00	1:05	1:13	1:17

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 4. Cloud Transmission Values from Irradiance Measurements.

Data Acquisition Period: 9/8/79; 23:40 - 9/9/79; 2:15

Laser Position \ Sylvania Run #		171	172	173	174	175	176	177
A	TRANSMISSION	--	0.481	0.817	0.604	0.442	0.773	0.697
B		--	--	0.913	0.622	0.495	0.773	0.693
C		0.422	0.487	0.942	0.639	0.531	0.773	0.691
D		0.426	0.486	--	0.663	0.571	0.770	0.686
E		0.431	0.478	--	0.717	0.633	0.765	0.682
F		0.448	0.463	--	0.740	0.688	0.726	0.676
G		0.458	0.460	--	0.755	0.709	0.708	0.674
H		--	0.460	--	0.766	0.730	0.679	0.670
J		0.467	0.461	--	0.766	0.764	0.645	0.650
Approximate Time (hr)		9/8/79 23:40	23:46		23:58	24:07	24:12	24:18

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 4. Cloud Transmission Values from Irradiance Measurements (continued).

Data Acquisition Period: 9/8/79; 23:40 - 9/9/79; 2:15

Laser Position \ Sylvania Run #		178	179	180	181	182	183	188
A	TRANSMISSION	0.458	--	0.876	0.480	0.352	0.885	--
B		0.440	0.989	0.811	0.472	0.330	0.923	--
C		0.439	0.964	0.784	0.468	0.325	0.937	--
D		0.443	0.948	0.750	0.465	0.329	0.952	--
E		0.468	0.936	0.704	0.464	0.351	--	0.841
F		0.527	--	0.668	0.465	0.393	--	0.836
G		0.564	--	0.651	0.466	0.416	--	0.806
H		0.610	--	0.636	0.466	0.443	--	0.798
J		0.695	0.989	0.617	0.464	0.517	--	0.701
Approximate Time (hr)		24:25	24:31	24:38	24:44	24:46	24:57	9/9/79 1:18

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 4. Cloud Transmission Values from Irradiance Measurements (continued).

Data Acquisition Period: 9/8/79; 23:40 - 9/9/79; 2:15

Laser Position \ Sylvania Run #		189	190	191	192	193	194	197
A	TRANSMISSION	0.659	--	0.833	0.710	0.341	0.950	--
B		0.839	--	0.852	0.668	0.371	0.804	--
C		--	--	0.876	0.644	0.389	0.980	--
D		--	--	0.914	0.625	0.415	--	--
E		--	--	--	0.594	0.458	--	0.924
F		--	0.801	--	0.556	0.498	--	--
G		--	0.767	--	0.544	0.520	--	--
H		--	0.744	--	0.531	0.544	--	--
J		--	0.710	--	0.515	0.622	--	--
Approximate Time (hr)		1:20	1:32	1:36	1:42	1:46	1:56	2:12

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 5. Cloud Transmission Values from Irradiance Measurements.

Data Acquisition Period: 9/12/79; 1:05 - 3:14

Laser Position \ Sylvania Run #	202	203	204	205	206	207	208
TRANSMISSION							
A	--	0.899	0.580	0.626	0.520	0.514	0.464
B	--	0.934	0.580	0.603	0.526	0.423	0.490
C	--	0.955	0.598	0.603	0.526	0.423	0.517
D	--	0.971	0.614	0.603	0.526	0.437	0.628
E	--	0.934	0.638	0.611	0.542	0.561	0.628
F	0.709	--	0.629	0.611	0.534	0.643	0.654
G	0.683	--	0.645	0.595	0.526	0.678	0.702
H	0.675	0.909	0.685	0.603	0.534	0.714	0.761
J	0.656	0.909	0.769	0.620	0.534	0.796	0.726
Approximate Time (hr)	1:13	1:19	1:25	1:31	1:37	1:43	1:50

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 5. Cloud Transmission Values from Irradiance Measurements (continued).

Data Acquisition Period: 9/12/79; 1:05 - 3:14

Laser Position \ Sylvania Run #		209	210	211	212	214	215
A	TRANSMISSION	0.620	0.649	0.994	0.905	--	0.986
B		0.569	0.709	--	0.889	--	--
C		0.552	0.750	--	0.961	--	--
D		0.463	0.821	--	0.970	--	--
E		0.393	--	--	--	--	--
F		0.349	--	--	--	--	--
G		0.349	--	--	--	--	--
H		0.343	--	--	--	0.983	--
J		0.343	--	--	--	0.903	--
Approximate Time (hr)		1:55	2:00	2:06	2:12	2:24	2:30

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 6. Results of τ from Irradiance Measurements.

Data Acquisition Period: 9/5/76, 2:15 - 23:25

Laser Position \ Sylvania Run #		93	94	96	97	100	104	105
A	OPTICAL THICKNESS	--	--	1.0	7.9	--	--	--
B		--	9.6	1.4	6.2	--	2.1	3.3
C		--	--	1.8	5.8	--	3.3	3.2
D		3.1	9.5	2.3	4.4	1.6	4.2	3.2
E		--	12.7	3.2	1.1	2.4	5.6	3.6
F		9.3	12.8	4.0	--	3.9	5.8	4.2
G		8.9	7.5	4.4	--	--	4.7	4.4
H		--	--	4.6	--	5.2	2.5	4.3
J		--	--	--	--	--	3.1	3.4
Approximate Time (hr)		21:15	21:17	21:33	21:41	22:02	--	--

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 7. Results of τ from Irradiance Measurements.

Data Acquisition Period: 9/6/79, 24:19 - 9/7/79; 2:50

Laser Position \ Sylvania Run #		114	115	116	117	118	119	120*	121	122	124
A	OPTICAL THICKNESS	--	--	4.3	--	--	12.5	59.9	13.8	10.5	--
B		--	--	5.2	11.9	8.1	11.2	55.4	15.8	9.4	--
C		--	--	--	10.8	9.7	10.9	49.4	17.1	8.8	--
D		1.4	--	--	8.6	10.9	11.3	42.7	18.8	8.1	--
E		--	1.9	--	4.9	11.5	12.3	33.3	21.0	7.2	1.6
F		--	--	--	--	9.0	13.1	27.1	--	7.2	--
G		--	--	1.6	2.6	--	13.4	24.3	--	7.2	--
H		--	--	--	1.2	--	13.8	22.5	18.1	7.2	--
J		--	--	1.2	--	9.8	15.3	20.0	19.3	8.1	--
Approximate Time (hr)		24:19	--	24:23	--	24:45	--	--	1:02	--	1:18

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

*Rain

Table 7. Results of τ from Irradiance Measurements (continued).

Data Acquisition Period: 9/6/79, 24:19 - 9/7/79, 2:50

Laser Position \ Sylvania Run #	126	127	128	129	130	132	134	136	138
OPTICAL THICKNESS									
A	--	6.5	5.2	36.9	--	--	2.1	4.7	6.6
B	1.6	--	5.8	32.7	--	--	15.5	--	1.7
C	6.9	--	6.1	30.5	--	--	18.3	--	--
D	9.5	--	3.9	28.9	1.5	--	--	--	--
E	12.9	--	4.8	25.9	2.7	2.0	--	3.2	--
F	7.3	--	8.0	21.7	2.6	--	--	--	--
G	8.5	--	8.4	19.7	2.5	--	--	1.5	--
H	9.3	--	8.5	18.7	3.0	--	--	5.9	--
J	12.0	--	8.7	15.7	2.9	--	--	10.9	--
Approximate Time (hr)		1:41	1:48	1:55	2:04	--	2:27	2:41	2:50

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 8. Results of τ from Irradiance Measurements.

Data Acquisition Period: 9/7/79, 22:38 - 9/8/79, 1:17

Laser Position \ Sylvania Run #		142	143	147	148	149	150	151
A	OPTICAL THICKNESS	--	17.8	38.0	14.1	25.[illegible]	--	--
B		12.7	18.9	38.1	11.9	22.0	--	5.4
C		--	18.7	38.0	11.0	20.0	1.0	--
D		12.8	18.0	35.7	11.0	18.9	1.0	--
E		12.4	15.2	26.9	10.6	16.4	1.2	--
F		11.3	8.6	11.1	12.1	13.6	1.3	--
G		10.7	7.5	9.9	13.9	12.1	1.2	--
H		10.3	6.8	10.7	15.6	10.4	1.2	--
J		9.0	5.6	15.5	19.5	7.6	1.0	--
Approximate Time (hr)		22:38	22:46	23:09	23:15	23:20	23:27	23:35

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 8. Results of τ from Irradiance Measurements (continued).

Data Acquisition Period: 9/7/79, 22:38 - 9/8/79, 1:17

Laser Position \ Sylvania Run #		152	154	155	158	159	160
A	OPTICAL THICKNESS	--	--	--	3.0	15.9	--
B		1.3	1.0	--	4.3	11.1	7.9
C		9.6	--	--	3.6	28.5	8.8
D		5.4	--	--	1.0	28.7	9.9
E		--	--	--	--	30.9	12.0
F		--	--	1.2	--	26.8	13.4
G		--	--	3.8	--	27.6	13.9
H		11.8	--	3.9	--	26.8	14.5
J		17.1	--	--	4.7	26.9	16.3
Approximate Time (hr)		23:41	23:53	24:00	00:18	00:24	00:30

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 8. Results of τ from Irradiance Measurements (continued).

Data Acquisition Period: 9/7/79, 22:38 9/8/79, 1:17

Laser Position \ Sylvania Run #		161	162	163	165	166	167	168
A	OPTICAL THICKNESS	31.9	--	--	20.9	24.4	34.5	19.6
B		27.9	19.4	--	19.5	26.2	25.7	20.5
C		27.5	20.4	--	18.8	27.6	23.1	19.6
D		27.0	22.0	2.8	17.9	28.1	22.5	18.1
E		31.0	24.9	--	16.2	29.5	22.5	12.6
F		26.4	25.1	--	14.9	30.2	22.2	2.4
G		25.6	24.2	--	14.5	30.8	20.8	5.5
H		50.0	22.6	--	14.2	32.1	17.9	5.2
J		--	20.9	12.6	14.4	32.5	17.3	--
Approximate Time (hr)		00:37	00:42	12:47	1:00	1:05	1:13	1:17

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 9. Results of τ from Irradiance Measurements.

Data Acquisition Period: 9/8/79, 23:40 9/9/79, 2:15

Laser Position \ Sylvania Run #		171	172	173	174	175	176	177
A	OPTICAL THICKNESS	--	9.9	1.4	6.1	12.9	2.7	4.5
B		--	--	--	5.6	10.3	2.7	4.6
C		12.5	9.6	--	5.2	8.8	2.7	4.6
D		12.3	9.7	--	4.6	7.4	2.8	4.7
E		12.0	10.0	--	3.4	5.6	2.9	4.8
F		11.1	10.7	--	2.9	4.2	3.6	5.0
G		10.6	10.9	--	2.6	3.8	4.0	5.0
H		--	11.0	--	2.4	3.3	4.7	5.1
J		10.2	10.8	--	2.4	2.7	5.5	5.6
Approximate Time (hr)		9/8/79 23:40	23:46		23:58	24:07	24:12	24:18

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 9. Results of τ from Irradiance Measurements (continued).

Data Acquisition Period: 9/8/79, 23:40 - 9/9/79, 2:15

Laser Position \ Sylvania Run #		178	179	180	181	182	183	188
A	OPTICAL THICKNESS	13.1	--	1.8	12.9	22.1	2.1	--
B		14.1	--	2.8	13.3	24.4	1.5	--
C		14.2	--	3.3	13.5	24.8	1.3	--
D		13.9	1.0	4.0	13.7	24.4	1.1	--
E		12.6	1.0	5.0	13.7	22.2	--	3.2
F		9.9	--	5.9	13.7	18.6	--	3.3
G		8.5	--	6.3	13.6	16.9	--	3.9
H		7.0	--	6.7	13.6	15.2	--	4.0
J		4.8	--	7.3	13.7	11.4	--	6.1
Approximate Time (hr)		24:25	24:31	24:38	24:44	24:46	24:57	9/9/79 1:18

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 9. Results of τ from Irradiance Measurements (continued).

Data Acquisition Period: 9/8/79, 23:40 - 9/9/79, 2:15

Laser Position \ Sylvania Run #		189	190	191	192	193	194	197
A	OPTICAL THICKNESS	7.4	--	3.8	6.4	25.8	2.1	--
B		3.4	--	3.4	7.5	22.9	4.5	--
C		--	--	3.0	8.2	21.2	1.7	--
D		--	--	2.4	8.8	19.2	--	--
E		--	--	--	9.8	16.3	--	2.6
F		--	4.2	--	11.3	14.1	--	--
G		--	4.9	--	11.8	13.0	--	--
H		--	5.4	--	12.3	12.0	--	--
J		--	6.2	--	13.1	9.0	--	--
Approximate Time (hr)		1:20	1:32	1:36	1:42	1:46	1:56	2:12

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

Table 10. Results of τ from Irradiance Measurements.

Data Acquisition Period: 9/12/79, 1:05 - 3:14

Laser Position \ Sylvania Run #		202	204	205	206	207	208	209	210
A	OPTICAL THICKNESS	--	3.9	3.0	6.5	7.0	9.3	4.3	3.9
B		--	3.7	3.6	6.3	10.9	8.2	5.7	2.6
C		--	3.5	3.6	6.3	10.9	7.2	6.3	1.8
D		--	3.1	3.6	6.3	10.2	3.9	9.7	1.0
E		--	2.5	3.4	5.8	5.4	3.9	13.4	--
F		--	2.7	3.4	6.0	3.3	3.3	16.5	--
G		1.0	2.4	3.8	6.3	2.5	2.3	16.5	--
H		1.1	1.6	3.6	6.0	1.8	1.2	17.0	--
J		1.5	--	3.2	6.0	--	1.8	17.0	--
Approximate Time (hr)		1:13	1:25	1:31	1:37	1:43	1:50	1:55	2:00

KEY

A. 15 000 yards inbound
B. 10 000 yards inbound
C. 7 500 yards inbound
D. 5 000 yards inbound
E. Directly overhead
F. 5 000 yards outbound
G. 7 500 yards outbound
H. 10 000 yards outbound
J. 15 000 yards outbound

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APPENDIX A

CORRECTION FOR USING A 45° ANGLE FIELD OF VIEW LIMITER WITH A LAMBERTIAN RECEIVER.

In the case of measurements with clouds, the irradiance intensity incident upon the horizontal surface of the collector is peaked along the vertical direction with a cos θ dependence for the intensity of light rays whose orientation differs from the zenith by an angle of θ.

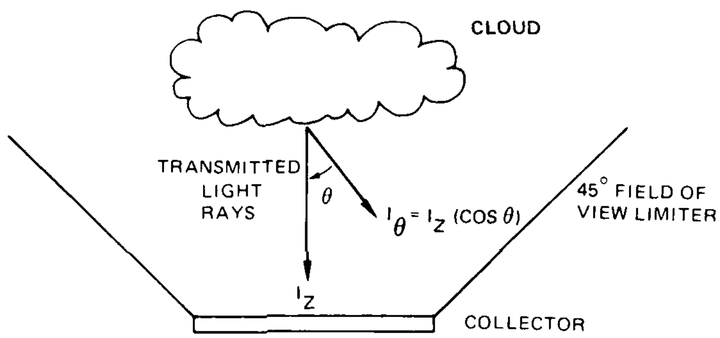

Figure A-1.

The total amount of integrated intensity, $I(\theta_L)$ received at the collector is proportional to:

$$I\ (\theta_L)\ \alpha \int_0^{2\pi}\int_0^{\theta_L} \cos\theta \sin\theta \, d\theta \, d\phi \qquad \text{(A-1)}$$

The solid angle is accounted for by the integration over sin θ dθ dϕ, where ϕ is the azimuthal angle, θ_L is the angle of the field of view limiter when measured from the normal.

Note that it is not necessary to normalize the irradiance measurements because a ratio between I(π/2) and I(π/4) would cause any factors common to both to cancel out. However, a constant of proportionality equal to 1/π is appropriate in order for the integrated irradiance value to equal 1 in the case when no field of view limiter is present.

$$I\left(\frac{\pi}{2}\right) = \frac{1}{\pi}\int_0^{2\pi}\int_0^{\frac{\pi}{2}} \cos\theta \sin\theta \, d\theta \, d\phi = 1 \qquad \text{(A-2)}$$

The cloud is assumed to subtend the field of view in this analysis although, in the experimental case, the irradiance values obtained represent an average of the sky over the field of view.

Next, we evaluate the integral in (A-1) for the unobstructed case, with $\theta_L = \pi/2$ and then for the experimental case when $\theta_L = \pi/4$.

$$I\,(\theta_L) \;\alpha\; 2\pi \int_0^{\theta_L} \cos\theta \sin\theta \, d\theta \qquad \text{(A-3)}$$

$$\int \cos\theta \sin\theta \, d\theta = \frac{\sin^2\theta}{2} \qquad \text{(A-4)}$$

Therefore:

$$I\left(\frac{\pi}{2}\right) = \pi \qquad \text{(A-5)}$$

and

$$I\left(\frac{\pi}{4}\right) = 0.500\,\pi \qquad \text{(A-6)}$$

$$\frac{I\left(\frac{\pi}{2}\right)}{I\left(\frac{\pi}{4}\right)} = 2 \qquad \text{(A-7)}$$

Thus the 45° field of view limiter is seen to occlude half of the light transmitted through the clouds and, as a result, a factor of 2 is obtained for correcting the experimental voltage data (which are proportional to irradiance).

APPENDIX B

LBS:sd
Ser 811/24
22 January 1979

MEMORANDUM

From: Code 8114
To: SETC File
Via: Code 811

Subj: Zenith Angle Dependence of Thick Cloud Transmittance

Ref: (a) L. B. Stotts, "Technical Comments on the Single Pulse Downlink Propagation Model Portion at the Third Interim OSCAR Report," NOSC MEMO Ser 811/560, dtd 2 January 1979.

(b) R. E. Danielson, D. K. Moore and H. C. van de Hulst, "The Transfer of Visible Radiation Through Clouds," J. Atmos. Sci., 26, No. 9, pp. 1078–87 (1969).

(c) E. A. Bucher, "Computer Simulation of Light Pulse Propagation for Communications Through Thick Clouds," Applied Optics, 12, No. 10, pp. 2391–2400 (1973).

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1. The purpose of this memorandum is to propose a new functional dependence on zenith angle for thick cloud transmittance. In particular, the author proposes that the thick cloud transmittance in the Navy Single Downlink Propagation Model be given by

$$\tau_c \propto A(\varphi_c) \, . \qquad (1)$$

where

$$A(\varphi_s) = \sum_{j=0}^{6} a_j \varphi_s^j$$

a_0 = 1.69
a_1 = -0.5513
a_2 = 2.7173
a_3 = -6.9866
a_4 = 7.1445
a_5 = -3.4249
a_6 = 0.6155

rather than by $\tau_c \propto (\cos \varphi_s)^{0.5}$ (ref (a)).

2. The zenith angle dependence of thick cloud transmittance has been modeled by Danielson et al (ref (b)) using radiative transfer techniques and reconfirmed by Bucher (ref (c)) using Monte Carlo simulation.

It was noted in reference (a) that the $(\cos \varphi_s)^{0.5}$ dependence for cloud transmittance now used in the Navy Downlink Propagation Model breaks down for zenith angles greater than 84°. Using a triangular factorization (least-square fit: ref (d)) of the X'X matrix composed of the tabular results given in reference (b), the author obtained the following polynomial expression for the zenith angle dependence of thick cloud transmittance:

$$A(\varphi_s) = \sum_{j=0}^{6} a_j \varphi_s^j \tag{3}$$

with

$a_0 = 1.69$
$a_1 = -0.5513$
$a_2 = 2.7173$
$a_3 = -6.9866$
$a_4 = 7.1445$
$a_5 = -3.4249$
$a_6 = 0.6155$

Figure B-1 is a plot of $A(\varphi_s)$ and the van de Hulst/Bucher results as a function of incident zenith angle. It is apparent that $A(\varphi_s)$ is a good approximation of the van de Hulst/Bucher results over the range between 0° and 90°. It is recommended that this expression be adopted in the Navy Single Pulse Downlink Propagation Model.

3. Any questions on the above should be directed to L. B. Stotts, Code 8114, X6858.

L. B. STOTTS

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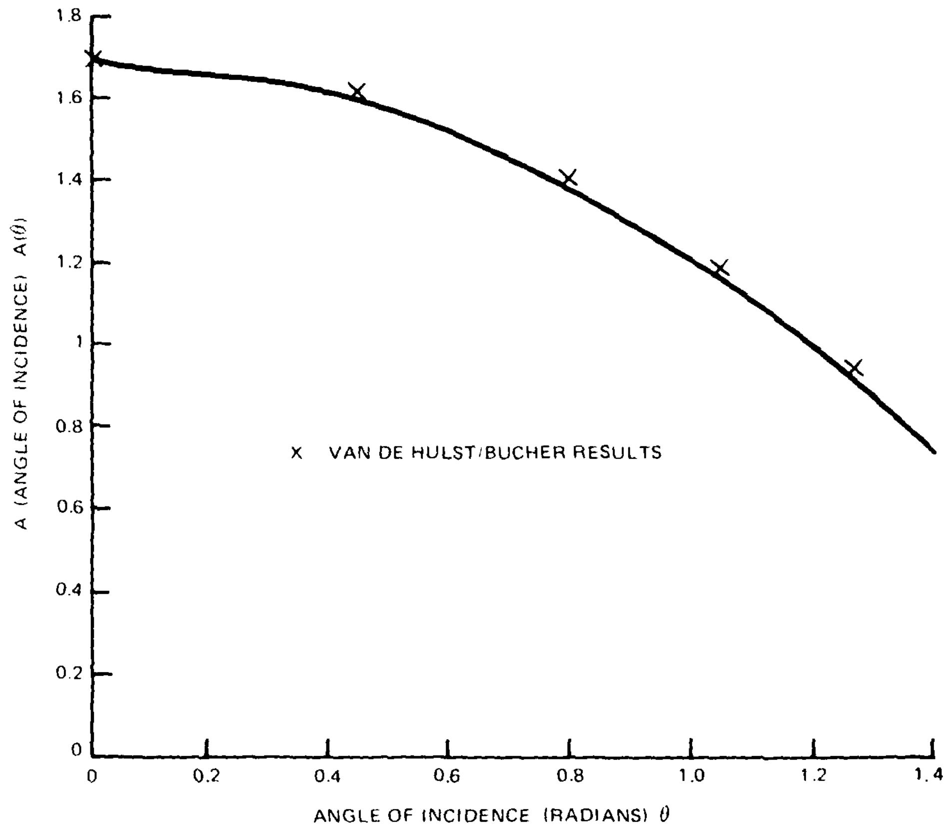

Figure B-1. Zenith angle dependence of thick cloud transmittance.

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